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Granulite Facies Metamorphism in the Ivrea Zone, N. W. Italy

by *Jane D. Sills**

Abstract

New mineral analyses are presented for a range of rock types from the Ivrea Zone (NW Italy). The pressure - temperature conditions of granulite facies metamorphism are estimated in order to test the hypothesis that the Ivrea Zone represents a section through the lower continental crust. Pressure estimates vary considerably along strike. The central part of the Ivrea Zone, in Val Sesia, gives a P–T of 750–800° C and 8 ± 0.5 kb, whereas metasediments in Val Strona further north give 750 ± 50° C but only 6 ± 1 kb. These pressures were calculated from gt-opx-plag-qz, gt-sill-plag-qz and gt-ol-plag assemblages. The granulite facies metamorphism was probably associated with the emplacement of a large mafic complex, which has only partially re-equilibrated to granulite facies conditions, with igneous textures locally preserved. In this complex garnet occurs as fringes between plagioclase and pyroxenes or olivine. There are a variety of olivine + plagioclase reaction coronas which probably developed during isobaric cooling from igneous temperatures. The pressure gradient across the Ivrea Zone suggests it was rotated to its present subvertical position after the peak of metamorphism. It is only in Val Sesia and possibly at Finero in the north that the pressures were high enough for the rocks to have come from the lowermost continental crust.

Keywords: Granulite facies, geothermometry, geobarometry, continental crust, Ivrea-Verbano Zone, NW - Italy

Zusammenfassung

Neue Mineralanalysen werden für eine Reihe Gesteinstypen der Ivreazone (N.W. Italien) vorgelegt. Die Druck-Temperatur-Bedingungen der Granulit-Fazies-Metamorphose werden berechnet, um die Hypothese zu überprüfen, dass die Ivreazone einen Abschnitt der unteren Kontinentalkruste darstellt.

Die Druckwerte schwanken erheblich der Streichrichtung entlang. Die mittlere Ivreazone, in Val Sesia, ergibt P-T-Bedingungen von 750–800° C und 8 ± 0.5 kb, im Gegensatz zu Metasedimenten in Val Strona (im Norden), die 750 ± 50° C aber nur 6 ± 1 kb ergeben. Diese Drucke werden von gt-opx-plag-qz, gt-sill-plag-qz und gt-ol-plag Paragenesen abgeschätzt. Die Granulit-Fazies-Metamorphose war wahrscheinlich mit der Intrusion eines grossen Mafitkomplexes verbunden. Dieser

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kam nur zum Teil mit den Bedingungen der Granulit-Fazies ins Gleichgewicht, die magmatischen Texturen sind stellenweise erhalten.

In diesem Komplex kommt Granat an der Reaktionszone zwischen Plagioklas und entweder Pyroxen oder Olivin vor. Es gibt verschiedene Olivin + Plagioklas Reaktionskronen, die sich wahrscheinlich während der isobarischen Abkühlung von den magmatischen Temperaturen entwickelten. Die Unterschiede in den Druckwerten über die Ivreazone deuten an, dass sie zu ihrer jetzigen fast senkrechten Lage nach dem Höhepunkt der Metamorphose umgedreht wurde. Nur in Val Sesia und vielleicht bei Finero waren die Drucke hoch genug, um eine Herkunft der Gesteine aus der untersten Kontinentalkruste zu erlauben.

Introduction

The Ivrea Zone, southern Alps, NW Italy is commonly considered to be a section through the lower continental crust (BERCKHEMER, 1969; MEHNERT, 1975; FOUNTAIN & SALISBURY, 1981), although NEWTON & PERKINS (1982) and WOOD (1983) suggest that the pressures are too low for it to represent the lowermost continental crust. One important constraint can be placed on this model by attempting to quantify the pressure-temperature, and in particular the pressure, conditions of metamorphism.

The Ivrea Zone (Fig. 1) consists of a steeply dipping sequence of metasedimentary and metabasic rocks with ultrabasic lenses, separated from the Alps proper by the Insubric line. The metasedimentary sequence comprises metapelites and some metacarbonates with interbanded amphibolites. These are intruded by a large mafic body – the ‹basischer Hauptzug› of LENSCH (1971) which is best exposed in Val Sesia (Figs. 1 and 2) and has been interpreted as a layered stratiform complex (RIVALENTI et al., 1975, 1981).

The grade of metamorphism increases from amphibolite facies in the SE to granulite facies in the NW. Several studies have been made of this prograde transition, particularly for the metasedimentary sequences exposed in Val Strona and Val d'Ossola (Fig. 1: MEHNERT, 1975; SCHMID & WOOD, 1976; ZINGG, 1980; HUNZIKER and ZINGG, 1980). These various studies have proposed several causes for the granulite facies metamorphism which can be summarized as follows:

(1) the prograde transition from amphibolite facies to granulite facies is just due to increasing depth of burial (MEHNERT, 1975)

(2) granulite facies metamorphism was caused by the emplacement of a large mantle wedge, now represented by the Balmuccia and Finero peridotite complexes (SHERVAIS, 1979)

(3) granulite facies metamorphism was caused by the intrusion of the large mafic complex into sediments already undergoing amphibolite facies metamorphism. SCHMID & WOOD (1976) calculated the range in P and T across a section in Val d'Ossola and concluded that the range was too small for it to be a near vertical section through the crust and so suggested that the sediments had al-

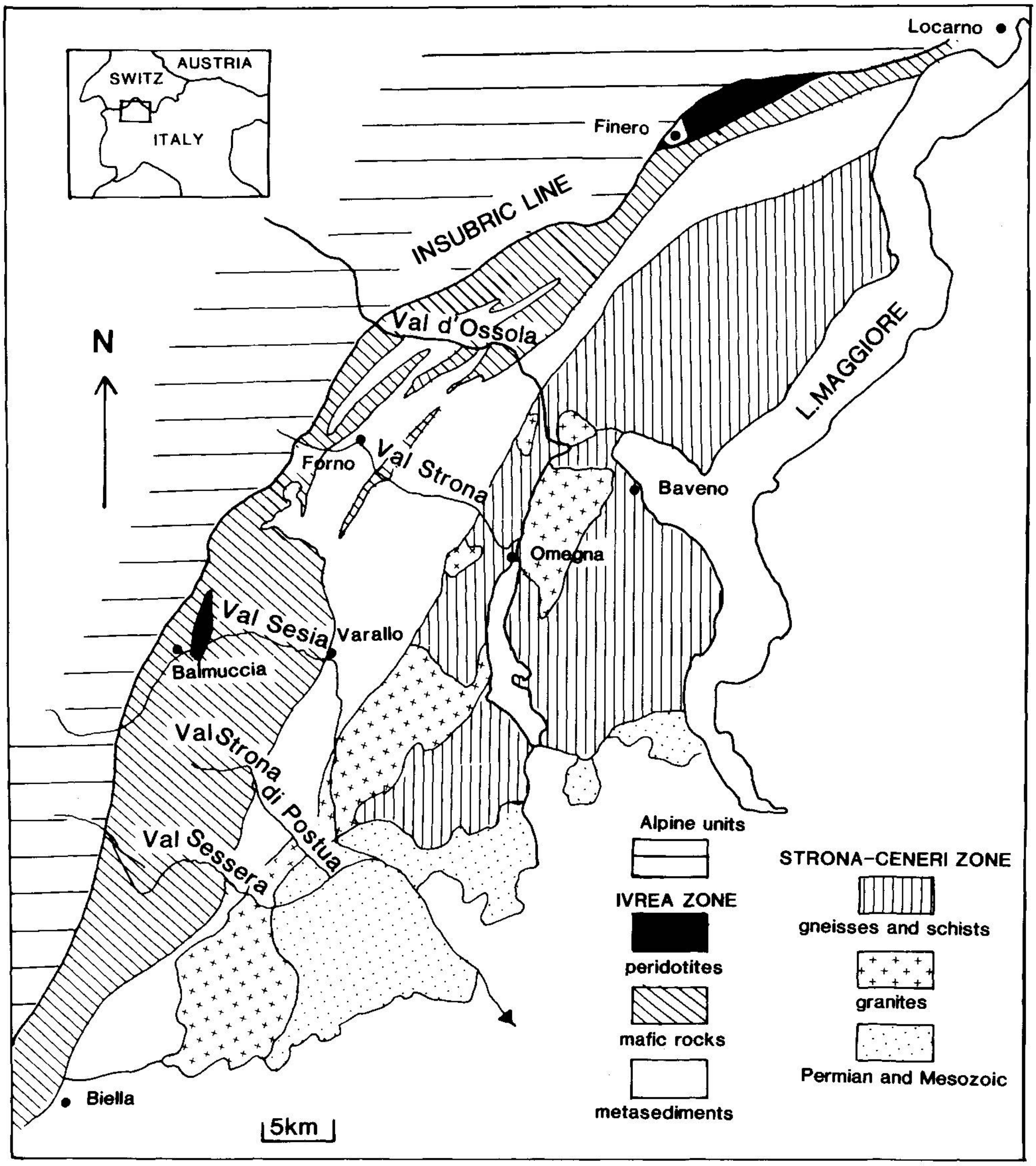

Fig. 1 Sketch map of the Ivrea Zone (from ZINGG, 1980) showing localities mentioned in the text.

ready been tilted to almost their present sub-vertical position before emplacement of the mafic magmas. However the internal stratigraphy of the layered complex in Val Sesia, which also appears to be sub-vertical, led HUNZIKER & ZINGG (1980) to conclude that the rotation occurred after emplacement of the magma. RIVALENTI et al. (1981) postulated that the layered complex has not suffered a pervasive granulite facies metamorphism but has merely partially re-equilibrated to the ambient granulite facies conditions during cooling.

In order to discriminate between these various models it was felt that a further study was warranted partly as better calibrated geobarometers have recently become available (e.g. NEWTON & HASELTON, 1981; NEWTON & PERKINS, 1982; BOHLEN et al., 1983).

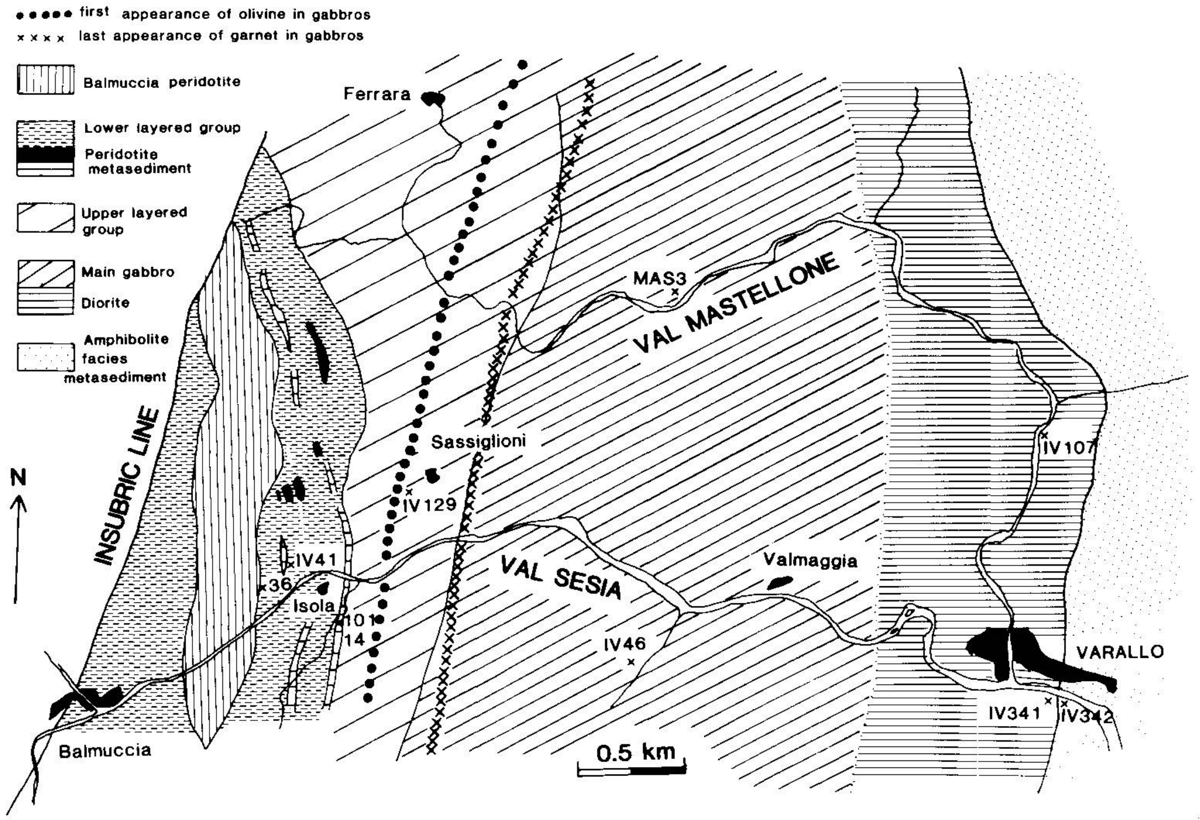

Fig. 2 Sketch map of the Val Sesia section (after RIVALENTI et al., 1981). × IV36 etc. refer to sample localities.

In this paper the sections exposed in Val Sesia and Val Strona are studied in detail with the aim of quantifying variations in pressure and temperature across the sections. All samples were collected by the author and the location of key samples referred to in the text is shown on Fig. 2.

Geological Setting

The Val Sesia section was described in detail by RIVALENTI et al. (1975, 1981). From NW to SE is can be summarised as follows (Fig. 2):

(1) the Insubric Line
(2) highly sheared metagabbros
(3) the Balmuccia peridotite, commonly interpreted as mantle lherzolite (e.g. ERNST, 1978)
(4) a layered series, the lower layered series (LLG) of RIVALENTI et al.(1975) comprising pyroxenites and gabbros with minor peridotites and harzburgites
(5) intercalations of granulite facies metasediment within the LLG; these are generally a few metres wide, but one prominent and very continuous layer, 50–100 m wide, occurs near the village of Isola (Fig. 2)
(6) a further layered series, the upper layered series (ULG) of RIVALENTI et al. (1975) comprising plagioclase-rich gabbros with minor anorthosite and pyroxenite layers, extending as far east as the village of Sassiglioni (Fig. 2)
(7) a fairly homogeneous gabbro which reaches maximum thickness of about 5 km; this is the main gabbro (MG) of RIVALENTI et al. (1975)
(8) the main gabbro grades upwards into diorites by the gradual increase in modal biotite. Near the contact with the metasediments there are angular sedimentary xenoliths
(9) amphibolite facies metasediment.

The whole suite of mafic rocks was interpreted as a layered complex by RIVALENTI et al. (1975, 1981), but it is more likely that the lower layered series developed from a completely different magma to the ULG, MG and diorite (SILLS, unpublished data).

The Val Strona and Val d'Ossola sections were described in detail by MEHNERT (1975) and SCHMID & WOOD (1976). Here amphibolite facies metasediments dominated by biotite with minor amounts of sillimanite become granulites by the gradual replacement of bi + sill by gt + kspar (SCHMID & WOOD, 1976) (for abbreviations see Table 1). A zone of migmatites occurs along the transition between amphibolite and granulite facies (MEHNERT, 1975). In Val Strona garnetiferous metagabbros, occurring near the Insubric line, are related to the cumulate layered complex in Val Sesia (CAPEDRI et al., 1977). The amphibolites (and a few basic granulites), which were intercalated with the metasediments before the emplacement of the main mafic complex, probably originated as ocean floor basalts (SILLS & TARNEY, 1984). It is quite probable that different tectonic levels are exposed in the different valleys.

Petrography and Mineral Chemistry

Details of analytical techniques and representative mineral analyses are given in Tables 2–5.

VAL SESIA

a) Metabasites

As discussed above, SCHMID & WOOD (1976) and HUNZIKER & ZINGG (1980) suggested that the granulite facies metamorphism was caused by the emplacement of the mafic complex. A corollary to this is that the mafic rocks crystallised in the mid to lower crust. The geochemical evidence (RIVALENTI et al., 1975) suggests that the LLG fractionated at moderate pressures and textural evidence suggests only partial equilibration of igneous assemblages to granulite facies conditions.

(i) The lower layered group comprises deformed and foliated rocks dominated by pyroxenites and pyroxene-rich gabbros. They contain coarse (0.5–1 cm) pinkish brown clinopyroxene with exsolution lamellae of opx, brown square shaped minerals (possibly rutile) and occasional plagioclase. Clinopyroxene contains 7–8.5 wt. % Al_2O_3, 1–1.5 wt.% TiO_2 and <0.3 wt.% Cr_2O_3 with mg ranging from 70–75. Opx occurs either as small grains at the margins of cpx or as larger grains with exsolution lamellae. It has 5.2–6.5 wt.% Al_2O_3 with mg ranging from 70–75. Plagioclase is always less than about 40 modal % and is often interstitial with a composition of about An_{50}, but in some mg-rich gabbros (eg. IV41; Table 2) it is about An_{84-88}. Green spinel, magnetite, ilmenite and an orange-brown kaersutite also occur. Garnet, present in many gabbros, has about 17–19 mol.% grossular, 42–45 mol.% almandine, 33–35 mol.% pyrope and about 2% spessartine. It has two modes of occurrence:

(a) as fringes, up to 2 mm thick, between clinopyroxene and plagioclase (Fig. 3a). Small grains of orthopyroxene and opaque oxide often occur near this garnet, suggesting the following reaction:

$$\text{opx} + \text{plag} = \text{cpx} + \text{gt} \qquad (1)$$

(b) more commonly garnet rims opaque oxides, either ilmenite or magnetite or composite grains, usually adjacent to plagioclase, but sometimes enclosed in clinopyroxene. This suggests the following reaction (using measured compositions)

$$6\ \text{opx} + 6\ \text{an} + 2\ \text{mgt} = 3\ \text{cpx} + 3\ \text{gt} \qquad (2)$$

$$\underset{\text{opx}}{6\ Mg_{1.3}Fe_{0.6}Al_{0.2}Si_{1.9}O_6} + \underset{\text{plag}}{6Na_{0.04}Ca_{0.96}Al_{1.96}Si_{2.04}O_8} + \underset{\text{mgt}}{2\ Fe_2O_3} =$$

$$\underset{\text{cpx}}{3\ Na_{0.08}Ca_{0.88}Mg_{0.66}Fe_{0.28}Al_{0.26}Si_{1.84}0_6} + \underset{\text{gt}}{3\ CaMg_2Fe_3Al_4Si_6O_{24}}$$

Plagioclase, adjacent to garnet, often has Ca-depleted rims suggesting that the anorthite molecule has been consumed in the garnet forming reactions. When the bulk-rock mg number is > 65 garnet only forms along opq-plag contacts and when mg > 70 garnet does not occur at all.

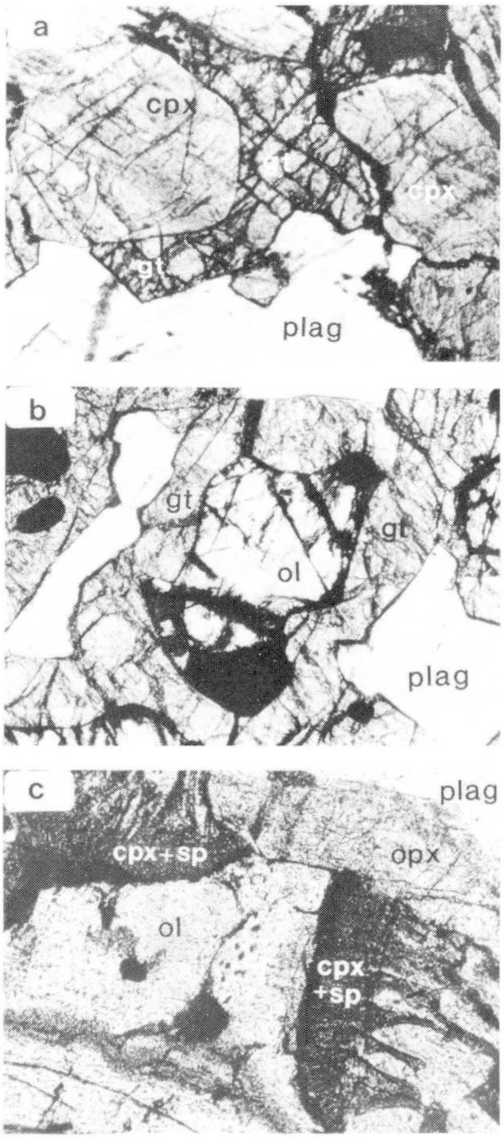

Fig. 3 (a) garnet forming between cpx and plag. Sample IV36, lower layered group. Field of view 3.2 mm across. (b) garnet forming between ol and plag. Sample IV129, upper layered group. Field of view 3.2 mm across. (c) ol + plag = opx + cpx + sp reaction. Sample MAS3. Field of view - 2 mm across.

(ii) ULG. The gabbros, occurring as far east as Sassiglioni, are plagioclase-rich with a polygonal equigranular texture and unlike the LLG gabbros may contain olivine. They have the following assemblage:

$$\text{plag} + \text{opx} + \text{cpx} \pm \text{ol} + \text{hb} \pm \text{gt} + \text{opq} \pm \text{bi} \pm \text{sp}$$

Minerals have similar compositions to the lower layered group. Garnet forms fringes between clinopyroxene and plagioclase as in the LLG, but it also occurs as rims, 1-2 mm thick between olivine and plagioclase (Fig. 3b), suggesting the following reaction:

$$\text{plag} + \text{ol} = \text{gt} \qquad (3)$$

However, in order to produce garnet, which is more Fe-rich than the olivine (see IV129; Table 2), opaque oxide must be included in this reaction.

(iii) Main gabbro. This is a fairly homogeneous series of plagioclase-rich gabbros. The lower part of the series comprises medium grained plag + opx + cpx + hb ± sp ± opq gabbros which have a polygonal texture with pyroxenes 1-3 mm and plagioclase 1-5 mm across. Higher up the sequence igneous textures are often preserved with lath-shaped plagioclase up to 1 cm long with hornblende and pyroxene, poikilitically enclosing plagioclase. Olivine occurs as small rounded grains up to 3 mm across, but usually much smaller. In general the MG has the following assemblage:

plag + opx + cpx + sp ± ol + opq + hb ± bi

Representative mineral analyses from one olivine-bearing sample are given in Table 3. Olivine has mg ranging from 50-66 with NiO below the detection limit of the energy dispersive system (<0.25 wt. % NiO). Clinopyroxene is moderately aluminous (Al_2O_3 ranging from 4-6.5 wt. %), TiO_2 ranges from 1.0-0.3 wt. %, both Ti and Al in general decreasing up the stratigraphic section. They have mg ranging from 60-78. Orthopyroxene has Al_2O_3 ranging from 2.5 to 4.5 wt. % and mg from 58-71. Hornblende has TiO_2 as high as 6.5 wt. %. Spinels are green pleonastes with Cr_2O_3 below detection. Plagioclase varies considerably, ranging from An_{50} to An_{85}.

There are well developed reaction coronas between olivine and plagioclase (Fig. 3c; CAPEDRI, 1971), which comprise a symplectitic intergrowth of green spinel and cpx, with grains of opx, although there are also intergrowths of opx + sp. This suggests the reaction:

ol + plag = opx + cpx + sp (4)

Vermicular intergrowth of either pyroxene and spinel are common and indicate the former presence of olivine. One sample (MAS 3; Fig. 2) does have some stable ol-plag contacts, but ol-plag reaction textures are also present. The approximate eastern limit of garnet and the first appearance of olivine in gabbros (or intergrowths of sp + pyx presumed to mark the former presence of olivine) are shown on Fig. 2.

(iv) Diorites. The MG grades gradually into diorite by the increasing abundance of biotite and hornblende. The diorites are olivine free and only contain garnet within a few metres of the contact with the metasediments. Assemblages are.

plag ± opx ± cpx + hb + bi
plag ± opx + hb + bi ± qz
plag + hb + bi ± qz
plag ± hb + bi + qz ± gt ± kspar

Plagioclase varies from about An_{70} to An_{35-40} near the contact with the metasediments. Both cpx and opx have much lower Al_2O_3 contents (1-2 wt. % and 0.3-3 wt. % respectively). The mg values range from 50-66 in cpx and 35-58 in opx. Large garnets (Table 3) have high MnO, low MgO and may be zoned with Ca-rich margins.

Pyroxenes are generally enclosed in hb and are rarely in contact with plag (ZINGG, 1980). The hb either developed after crystallisation by a reaction between pyx and plag, or it crystallised directly from the magma, i.e. primary igneous hornblende. Within a few m of the contact with the metasediments, large (up to 1.5 cm) garnets occur, along with orthoclase and quartz. These diorites, although containing the assemblage plag + bi + gt + qz are easily distinguishable from metasediments with a similar assemblage because of their much weaker foliation and coarser grain size. Biotite in diorites has higher TiO_2 and BaO contents than in the metasediments. Garnet has up to 4.5 wt. % MnO in the diorites but less than 1 wt. % in the sediments (Tables 3 and 4).

b) Metasediments

Granulite facies metasediments occur as layers within the LLG (Fig. 2). They are similar to granulite facies metasediments from elsewhere in the Ivrea Zone, comprising well banded gneisses with the following assemblages:

qz + plag + perthite + gt + opx
qz + plag + perthite + gt + sill
opx + cpx + plag ± qz

The two pyroxene granulites are quite distinct from the layered complex being much finer grained with an equigranular polygonal texture. Representative analyses are given in Table 4.

Amphibolite facies gneisses near the contact with the diorite consist of an extremely heterogeneous mixture of metapelite, amphibolite and marble (for a more detailed account see ZINGG, 1980). Within a few metres of the contact there are abundant migmatites. The metapelites are generally medium to fine grained well foliated gneisses comprising:

plag + qz + gt + bi + cord ± anth ± sulphides + opq
plag + qz + gt + bi + opq

VAL STRONA METASEDIMENTS

The lower part of the Strona valley contains biotite + muscovite gneisses (MEHNERT, 1976; ZINGG, 1980) but all the samples for this study are from above the K-feldspar isograd (ZINGG, 1980). The pelitic gneisses contain gt–bi–qz with one or more of the following phases, plag, kspar, sill, ilmt, sulphides, rutile, graphite and very rarely opx. Further south in Val Strona di Postua and Val Sesia, opx is more abundant in metapelites. The increase in metamorphic grade from SE to NW is reflected in an increase in modal garnet at the expense of biotite and an increase in the proportion of coarse prismatic sillimanite relative to fibrolite. A common granulite facies assemblage is gt + plag + sill ± kspar + ilmt + rutile + graphite. These samples may contain >75% sill + gt, with only traces of qz, possibly being restites.

The increase in garnet has been ascribed to the reaction:

$$bi + sill + qz = gt + kspar + H_2O$$

(SCHMID & WOOD, 1976). This biotite breakdown causes an increase in modal ilmenite and rutile. Some samples show the reverse of this reaction with large garnets being retrogressively replaced by bi + sill + qz. In Val Strona di Postua one garnet is being replaced by epidote + sill + qz, possibly as the result of a reaction between garnet and plagioclase. In the transition zone between amphibolite facies and granulite facies assemblages blebs of myrmekite, replacing kspar, are quite common.

Near Forno (Fig. 1) traces of previously unrecorded orthopyroxene have been found in a metapelite (IV383, Table 5), as well as bi + qz intergrowths, often associated with myrmekite. In the metapelites biotite generally occurs as quite large flakes, up to 0.5 cm long, with few inclusions. These bi + qz intergrowths have probably resulted from the breakdown of an earlier mineral assemblage, possibly containing opx. A reaction could be:

$$opx + 4kspar + 4H_2O = 2bi + 10qz$$

Representative mineral analyses for all the samples used for pressure - temperature calculations are given in Table 5. The broad changes in biotite and garnet composition with metamorphic grade reported for Val d'Ossola by SCHMID & WOOD (1976) are confirmed by this study. In general the mg-values for both biotite and garnet increase with metamorphic grade, the TiO_2 content of biotite increases and the MnO content of garnet decreases. Ilmenite, which is more abundant in granulite facies assemblages, may contain up to 5 wt. % MnO. Biotite inclusions in garnet have higher TiO_2 and mg-values than biotites at the edge of garnet grains as noted by SCHMID & WOOD (1976).

Pressure Temperature Conditions

A variety of estimates for the P–T conditions of granulite facies metamorphism in the Ivrea Zone have already been made. Temperatures of 850–950° C were obtained for the metamorphic equilibration of the mafic complex (SHERVAIS, 1979; RIVALENTI et al., 1981) with an estimate of pre-exsolution temperatures of 1000–1200° C. Pressure estimates for equilibration of the complex range from 6–11 kb, with a preferred value of 8 kb (RIVALENTI et al., 1981). SCHMID & WOOD (1976) proposed pressures in the range 9–11 kb for the metasediments in Val d'Ossola, but the model of NEWTON & HASELTON (1981) suggests a pressure of only 6 kb, calculated using their data. HUNZIKER & ZINGG (1980) propose pressures from 4.7–10 kb for the metasediments in Val Strona and Val d'Ossola. Temperature estimates also vary widely, with HUNZIKER & ZINGG (1980) calculating a temperature range of 540–820° C, increasing towards the Insubric line. SCHMID & WOOD (1976) suggest temperatures were in the range 700–820° C based on the reaction bi + sill + qz = gt + kspar + H_2O, assuming aH_2O was just sufficient to cause melting.

In this study new data, along with recent formulations of geothermometers and geobarometers, allow the P–T conditions to be defined more precisely. Pressures and temperatures are calculated from opx + cpx + plag ± gt ± ol ± sp assemblages in the metabasic rocks as well as from metasediments from Val Sesia, Val Strona, and two localities further south, Val Strona di Postua and Val Sessera (Fig. 1). The pressure estimates are given in Fig. 4.

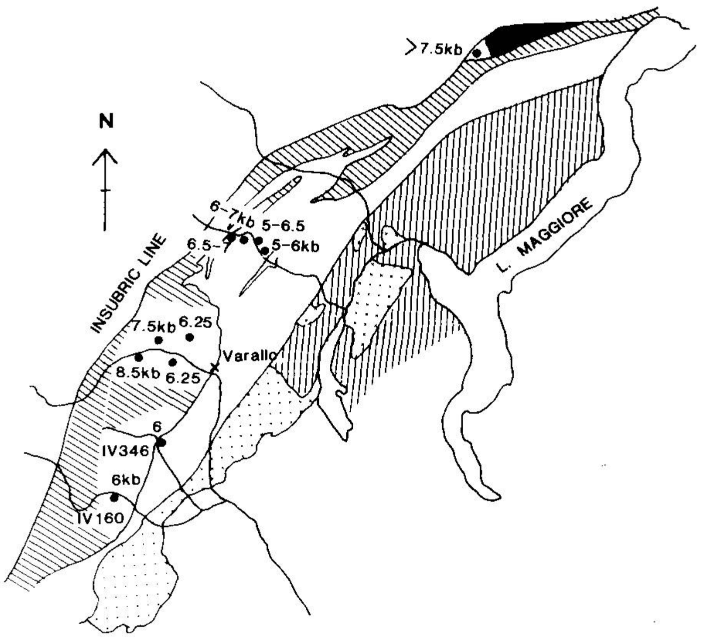

Fig. 4 Sketch map (as Fig. 1) showing pressure estimates.

VAL SESIA

In the lower layered group, upper layered group and main gabbro, two pyroxene temperatures range from 830–720° C (WELLS, 1977) and 860–710° C (WOOD & BANNO, 1973). These temperatures tend to correlate slightly with mg of the pyroxenes. LINDSLEY (1983) temperatures are more consistently within the range 750–800° C for both opx and cpx with the exception of the Al–Ti-rich pyroxenes from the LLG which give anomalously high clinopyroxene temperatures of 950–1050° C. Opx temperatures are still 750–800° C. Garnet-clinopyroxene pairs give temperatures in the range of 850–900° C (ELLIS & GREEN, 1979) if all the Fe is calculated as FeO, but if an estimate of Fe^{3+} is made, temperatures are reduced to 700–820° C. The lower temperatures may be due to an overestimation of the Fe^{3+} content due to the imprecise Na analyses obtained by the energy dispersive technique. Sample IV129, where wavelength dispersive analyses were obtained, gives temperatures of 750° C, in good agreement with the two pyroxene temperatures. In summary, the Fe-Mg exchange between coexisting opx–cpx–gt ceased at about 750 ± 50° C., slightly lower than the temperatures estimated by RIVALENTI et al. (1981) and SHERVAIS (1979).

Pressure, for the lower part of Val Sesia, has been estimated from the assemblage opx + gt + plag + qz (NEWTON & PERKINS, 1982) from a metasediment (sample IV101, Table 4) near the village of Isola. This gives a pressure of 8.3–8.9 kb at 800° C. Two pyroxene temperatures from a metabasite (IV14, Table 4) about 20 m from sample IV101 are between 800 and 825° C for all three models (WELLS, 1977; WOOD & BANNO, 1973; Lindsley, 1983). Similar pressures, about 0.5 kb higher, are obtained using the formulation of BOHLEN et al. (1983). Unfortunately the gabbros from the layered complex are all undersaturated (with respect to SiO_2) so this geobarometer cannot be applied. SHERVAIS (1979) presents analyses of a gt + sill + plag + qz gneiss from the same area as IV101 which gives a pressure of about 11.5 kb using the geobarometer of NEWTON & HASELTON (1981).

Pressures for the mafic complex can be estimated from the reaction ol + plag = gt (reaction 3). Experiments have been performed on the Fe-end member system (BOHLEN et al., 1983) and following their activity models, a pressure of 7 kb at 700° C and 8 kb at 800° C is obtained for the sample IV129 (Table 2). These pressures are 0.5–1 kb lower than those obtained from the model of WOOD (1975). JOHNSON & ESSENE (1982) have modelled the Mg-end member reaction from a variety of experimental data, which similarly yields pressures of about 7 kb for IV129.

Reaction 4, ol + plag = opx + cpx + sp, has been investigated experimentally by several authors (OBATA, 1976, HERZBERG, 1978) and a P–T curve for the Mg-end member reaction is given in JOHNSON & ESSENE (1982). The activities of the end members in the MG-rocks (eg. MAS 3, Table 3) are such that the equilibrium constant is very nearly unity. This reaction probably occurred at about 6–6.5 kb at 750° C (JOHNSON & ESSENE, 1982). Both reactions 3 and 4 could have occurred during isobaric cooling from igneous temperatures, a model often used to account for ol + plag reaction textures (eg. GRIFFIN, 1971), although a pressure increase from lower temperatures could also produce the coronas.

Garnet only occurs in the ol + plag reaction coronas near Sassiglioni (Fig. 2), whereas sp + opx + cpx occurs higher up the section. Reaction 3 suggests pressures of 7–7.5. kb and reaction 4, 6–6.5 kb. This pressure difference is likely to be real, rather than a compositional effect, because the mg-numbers of the samples with garnet-bearing coronas and those with opx + cpx + sp coronas are not sufficiently different for compositional factors to have controlled the distribution of garnet growth.

Gt-bi-plag-qz and gt-cord-anth-plag-qz gneisses occurring near the contact with the diorites give temperatures of 600-650° C from both gt-bi Fe-Mg exchange thermometry (FERRY & SPEAR, 1978; THOMPSON, 1976) and from gt-cord Fe-Mg exchange thermometry (HOLDAWAY & LEE, 1977; THOMPSON, 1976). These temperatures are 100-150° C lower than those estimated from granulite facies metasediments at Isola, 10 km further west. The diorites contain a green hornblende whereas the gabbros contain a brown Ti-rich hornblende, also suggesting higher temperatures in the gabbros. One diorite sample contains the assemblage plag + qz + hb + bi + gt + opx, which gives pressures of 3-4 kb using the NEWTON & PERKINS (1982) geobarometer, but it is not certain that the garnet and opx are in equilibrium, and the garnets contain 4-5 wt. % MnO, which is not considered in the activity model.

OTHER AREAS

Pressure and temperature estimates for metasedimentary gneisses are summarised in Table 6 and plotted on Fig. 4. Pressure estimates range from 4.5-7 kbar, distinctly lower than IV101, near the base of the layered complex in Val Sesia.

Temperatures are less well defined, as the only geothermometer that can be applied is the gt-bi Fe-Mg exchange geothermometer (FERRY & SPEAR, 1978; THOMPSON, 1976) which often gives erratic results, especially if the TiO_2 and octahedral Al contents of the biotite are high (BOHLEN & ESSENE, 1980). HUNZIKER & ZINGG (1980) report a gradual temperature increase from 580-820° C towards the Insubric line and although, there is a slight tendancy for temperatures to increase (Table 6), the range of values within any one sample is high. Unfortunately to obtain a precise pressure from the gt = sill + plag + qz geobarometer (NEWTON & HASELTON, 1981) a reasonable temperature estimate is required.

Granulite facies metapelites contain the assemblage gt-sill-rutile-ilmt-qz which is a reliable geobarometer with a low dP/dT (ESSENE, 1982). This gives a pressure of about 6 kb for IV160 and 6.5-7.1 kb for IV384 (Table 6). Temperatures of about 800° C for IV160 and 750° C for IV384 are then obtained from the plag = sill + qz + gt reaction using the above pressures. These temperatures are consistent with gt-bi temperatures from the same samples and with two pyroxene and gt-cpx temperatures from nearby metabasic rocks.

The data in Table 6 suggest temperatures in the range 650-750° C for IV381 and IV383, consistent with the occurrence of migmatites. The temperature estimate of 710° C (SCHMID & WOOD, 1976) seems reasonable. The data do not allow any possible temperature gradient across strike from IV385 to IV384 to be quantified.

The granulite facies metamorphism in the lower part of Val Sesia occurred at 750–800° C and 8–8.5 kb, but the granulite facies metamorphism in the metapelites exposed in Val Strona and in the southern valleys, where the mafic complex is less well exposed, occurred at about 750 ±50° C but at significantly lower pressures of 6 ±1 kb. There has been some subsequent retrogressive replacement of garnet and orthopyroxene-bearing assemblages by bi ± kspar ± sill + qz.

Discussion

The data presented above show that the pressures suffered by the metasediments in Val Strona are lower than those at the base of the layered complex in Val Sesia. Pressures of >7.5 kb are also indicated for sapphirine-bearing rocks near the mantle-lherzolite in Finero (Fig. 4; SILLS et al., 1983). The pressure difference, from ca 8.5. kb near the base of the complex (IV101) to 6.5 kb in the granulite facies metapelites elsewhere (IV346) is shown by the same geobarometer, so is likely to be real. The temperature estimates for granulite facies metamorphism do not differ so much between the base of the section in Val Sesia and the Val Strona section. This is consistent with the hypothesis that the granulite facies metamorphism was caused by the emplacement of the layered complex (SCHMID & WOOD, 1976) into metasediments already undergoing amphibolite facies metamorphism. The field evidence clearly shows that the layered complex was intruded into sediments. The high pressures from the base of the Finero section and the base of the Val Sesia section are consistent with derivation from the lower continental crust, but the lower pressures from the Val Strona section indicate an origin from intermediate crustal levels. This resolves the problem raised by WOOD (1983) and NEWTON & PERKINS (1982), who point out that the intermediate pressures of about 6 kb are not consistent with a lower crustal origin for the Ivrea Zone, as favoured by many authors (MEHNERT, 1975; FOUNTAIN & SALISBURY, 1981). These data suggest that the Val Sesia, and possibly Finero sections, do contain lower crustal rocks but that the other valleys are from higher crustal levels. This must mean that the uplift has not been uniform along the Ivrea Zone and that the Insubric line cuts across strike.

If the Ivrea Zone does represent an up-ended section through the lower continental crust, the pressure gradient should reflect this. The temperature gradient is unlikely to reflect a normal continental geotherm as the granulite facies metamorphism was caused by the emplacement of mafic magmas. From the data plotted in Fig. 4, it is possible to calculate a pressure gradient taking the pressure for the base of the Val Sesia section as 8±0.5 kb (IV101); the pressure near Sassiglioni as 7.25±0.5 kb (IV129); the pressure for MAS3 (and IV46; Fig. 2) as 6.25±0.5 kb and that for IV346 as 6±0.5 kb. Pressures at the top of the complex may have been as low as 4 kb.

The gradient from IV101 to the top of the complex (4 kb max over 7.5 km) is thus a maximum of 0.53 kb/km. From IV101 to IV346 (5.5 km) the gradient is 0.54–0.36 kb/km and from IV101 to MAS3 (4.3 km) it is 0.57–0.43 kb/km. In Val Strona the pressures are less well constrained, but the gradient from IV384 to IV385 is between 0.7 and 0.33 kb/km. These gradients are too high rather than too low, possibly suggesting tectonic thinning. However, imprecisions in calculating the pressure and probably more significantly closure problems mean that this type of calculation is fraught with difficulty. These data do suggest that there is a significant drop in pressure across the Val Sesia section, suggesting that the Ivrea Zone has been rotated to its present sub-vertical position after the granulite facies metamorphism.

Conclusions

Pressure and temperature estimates for the granulite facies metamorphism in the Ivrea Zone suggest that the lower part of the section exposed in Val Sesia, comprising metabasic rocks, was re-equilibrated at 750–800° C at 8±0.5 kb. The sedimentary sequences exposed in Val Strona and in valleys further south were metamorphosed at 750±50° C at 6±1 kb. This suggests that the lowermost part of the Ivrea Zone is composed of metabasic rocks which could have originated in the lower continental crust. The granulite facies metasediments in Val Strona did not come from such deep crustal levels and the granulite facies metamorphism was probably caused by the emplacement of the layered mafic complex. The pressure estimates, although not conclusive, suggest that the Ivrea Zone was rotated to its present position after the peak of metamorphism. The mafic rocks remained at high temperatures and pressures for long enough to allow development of the ol + plag reaction coronas which probably formed during isobaric cooling. The section exposed in Val Strona (e.g. MEHNERT, 1975) is thus not the most appropriate section to select as a section through the lower continental crust as it does not contain high pressure rocks.

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Appendix

Table 1 List of abbreviations used in the text.

qz	- quartz	bi	- biotite
plag	- plagioclase	sill	- sillimanite
kspar	- microcline or orthoclase	cord	- cordierite
opx	- orthopyroxene	anth	- anthophyllite
cpx	- clinopyroxene	opq	- opaque oxides
gt	- garnet	magt	- magnetite
sp	- spinel	ilmt	- ilmenite
hb	- hornblende	mg=	$100\ Mg/(Mg + Fe^{2+})$
ol	- olivine		

Table 2 Representative mineral analyses for two samples from the lower layered group (LLG) and one from the upper layered group (ULG). Location of samples is shown in Fig. 2. Analyses are averages of several points on unzoned grains. Analyses quoted to one decimal place were obtained by the energy dispersive system and those to two decimal places by the wavelength dispersive technique. Energy dispersive analyses were obtained using a LINK Systems 860 energy dispersive detector with a current of about 3na on cobalt.

Wavelength dispersive analyses were obtained using a Cambridge Instruments Microscan V electron probe with a current of about 20 na on copper. A range of natural and synthetic minerals and pure metal standards were used. In both cases data reduction was with the computer programme FRAME.

ROCK	IV36	LLG	gabbro		IV41	LLG	gabbro	IV129	ULG	gabbro	
MINERAL	Cpx	gt	plag	plag	opx	cpx	plag	plag	cpx	gt	ol
SiO2	48.4	39.7	56.1	57.3	51.9	49.1	46.5	55.27	49.48	39.84	36.4
TiO2	1.3	-	-	-	0.2	1.3	-	-	1.10	0.12	nd
Al2O3	7.0	21.7	28.5	27.4	5.2	7.2	33.7	27.59	6.61	21.98	nd
Cr2O3	nd	nd	-	-	0.2	0.2	-	-	nd	nd	nd
FeO	9.6	23.2	-	-	16.5	5.4	-	0.07	8.59	23.92	35.94
MnO	0.1	1.0	-	-	0.3	nd	-	-	0.09	0.70	0.24
MgO	11.1	8.9	-	-	25.4	13.0	-	-	11.55	8.85	29.13
CaO	21.4	6.9	10.1	9.1	0.6	23.0	17.8	10.60	21.13	6.49	nd
Na2O	1.2	-	5.5	6.2	-	0.9	1.6	5.48	1.49	-	-
K2O	nd	-	0.1	0.1	-	-	nd	0.25	-	-	-
TOTAL	100.1	101.4	100.3	100.1	100.1	100.1	99.6	99.26	100.04	101.81	101.71
mg	74.1	41.6			73.3	81.1			70.5	39.7	59.1
An			50.4	44.8			86.1	51.5			
No.of O	6	12	8	8	6	6	8	8	6	12	4
Si	1.816	3.002	2.510	2.563	1.875	1.812	2.148	2.509	1.845	3.000	0.994
Al	0.184	1.934	1.502	1.441	0.125	0.188	1.833	1.475	0.155	1.951	0.000
Al	0.125	-	-	-	0.221	0.125	-	-	0.135	-	-
Ti	0.037	-	-	-	0.005	0.036	-	-	0.031	0.006	0.000
Cr	-	-	-	-	0.006	0.006	-	-	0.000	0.000	0.000
Fe	0.301	1.467	-	-	0.499	0.167	-	0.002	0.268	1.507	0.821
Mn	0.003	0.064	-	-	0.009	-	-	-	0.003	0.045	0.006
Mg	0.621	1.003	-	-	1.367	0.715	-	-	0.642	0.994	1.186
Ca	0.862	0.560	0.485	0.437	0.023	0.911	0.882	0.516	0.845	0.516	0.000
Na	0.087	-	0.477	0.538	-	0.064	0.143	0.482	0.108	-	-
K	-	-	0.006	0.006	-	-	-	0.014	-	-	-

Table 3 Representative mineral analyses from the main gabbro (MG) and diorite. Location of samples is shown in Fig. 2. In IV341 (c) is the centre and (e) the edge of the same garnet grain. All other analyses are averages of homogeneous grains. The total for spinel in MAS3 includes 0.3. wt. % Cr_2O_3.

ROCK	MAS3	gabbro	MG					IV107	diorite			IV341	diorite		
MINERAL	plag1	plag2	ol	opx	cpx	sp	hb	plag	opx	cpx	bi	bi	plag	gt(c)	gt(e)
SiO2	48.1	50.6	36.4	51.6	49.7	-	39.7	52.9	51.1	51.8	33.5	33.9	57.5	37.1	37.2
TiO2	-	-	-	-	0.8	-	3.9	-	-	0.12	6.04	4.5	-	-	-
Al2O3	32.9	31.8	nd	3.2	5.4	58.2	14.7	29.9	0.9	1.2	14.3	16.4	26.3	21.2	21.1
FeO	-	-	35.7	20.5	7.0	30.4	12.4	-	26.4	11.1	19.9	23.1	-	28.6	25.6
MnO	-	-	0.6	0.5	0.4	0.3	nd	-	1.0	0.4	nd	nd	-	3.9	4.5
MgO	-	-	28.8	23.3	13.1	10.4	10.9	-	17.1	12.3	9.5	6.8	-	2.4	1.7
CaO	16.4	14.4	nd	0.5	22.1	-	11.5	12.4	1.7	22.5	nd	nd	8.5	7.5	10.2
Na2O	2.5	3.3	-	-	1.0	-	2.6	4.3	nd	0.32	0.12	nd	6.8	-	-
K2O	nd	nd	-	-	-	-	1.2	0.2	-	-	8.6	8.8	0.2	-	-
TOTAL	99.9	100.1	101.5	99.6	99.5	99.6	96.9	99.7	100.2	99.74	95.1	95.0	99.3	100.6	100.3
mg			59.0	67.0	77.0	37.9	61.0		51.9	66.3	46.0	34.4		13.0	10.6
An	78.4	79.7						60.7					40.4		
No. of O	8	8	4	6	6	4	23	8	6	6	22	22	8	12	12
Si	2.207	2.299	0.997	1.915	1.857	-	5.949	2.401	1.969	1.963	5.302	5.357	2.594	2.959	2.968
Al	1.779	1.703	-	0.085	0.143	1.900	2.051	1.599	0.031	0.037	2.698	2.643	1.398	1.993	1.984
Al	-	-	-	0.055	0.095	-	0.544	-	0.010	0.017	-	0.411	-	-	-
Ti	-	-	-	-	0.022	-	0.440	-	0.000	0.003	0.719	0.535	-	-	-
Fe	-	-	0.818	0.636	0.218	0.704	1.554	-	0.915	0.352	2.634	3.053	-	1.908	1.708
Mn	-	-	0.014	0.016	0.012	0.007	0.000	-	0.033	0.013	0.000	0.000	-	0.257	0.304
Mg	-	-	1.175	1.289	0.730	0.429	2.434	-	0.982	0.695	2.241	1.601	-	0.285	0.202
Ca	0.807	0.702	-	0.020	0.886	-	1.849	0.604	0.470	0.915	0.000	0.000	0.411	0.642	0.873
Na	0.222	0.291	-	-	0.720	-	0.755	0.279	-	0.024	0.000	-	0.595	-	-
K	-	-	-	-	-	-	0.229	0.012	-	-	1.737	1.774	0.012	-	-

Table 4 Representative mineral analyses from metasediments in Val Sesia. Location of samples is shown in Fig. 2. In IV101 gt(2) is a rim to ilmt.

ROCK	IV101				IV14		IV342			
MINERAL	gt	opx	plag	gt2	opx	cpx	gt	cord	bi	plag
SiO2	38.8	51.8	58.8	38.9	52.57	52.34	38.6	48.7	36.9	56.7
TiO2	nd	nd	-	nd	0.13	0.53	nd	-	2.0	-
Al2O3	21.8	2.7	25.6	21.9	1.71	3.30	21.9	33.1	17.7	27.5
Cr2O3	nd	nd	-	nd	0.14	0.27	nd	-	0.4	-
FeO	26.5	23.2	-	27.7	20.99	7.28	30.3	4.4	12.4	-
MnO	0.35	nd	-	0.6	0.34	0.17	0.6	-	nd	-
MgO	9.1	22.1	-	8.2	23.63	13.52	7.4	10.9	15.4	-
CaO	3.2	0.3	7.4	3.4	0.55	22.64	1.9	-	nd	9.2
Na2O	-	-	7.1	-	nd	0.58	-	-	0.5	6.4
K2O	-	-	0.2	-	-	-	-	-	8.4	nd
TOTAL	99.75	100.1	99.1	100.7	100.05	100.63	100.7	97.1	93.7	99.8
mg	38.0	62.9		34.5	66.7	76.7	30.2	81.5	69.2	
An			36.2							44.4
No.of O	12	6	8	12	6	6	12	18	22	8
Si	2.993	1.930	2.646	2.995	1.945	1.928	2.993	4.986	5.495	2.547
Al	1.981	0.070	1.357	1.982	0.055	0.072	2.001	3.993	2.505	1.456
Al	-	0.048	-	-	0.020	0.071	-	-	0.601	-
Ti	-	-	-	-	0.004	0.015	-	-	0.224	-
Cr	-	-	-	-	0.004	0.008	-	-	0.047	-
Fe	1.709	0.722	-	1.779	0.650	0.225	1.965	0.377	1.544	-
Mn	0.023	-	-	0.039	0.011	0.005	0.039	-	-	-
Mg	1.046	1.227	-	0.939	1.302	0.743	0.849	1.663	3.417	-
Ca	0.265	0.012	0.357	0.280	0.022	0.894	0.158	-	-	0.443
Na	-	-	0.619	-	-	0.042	-	-	0.142	0.557
K	-	-	0.011	-	-	-	-	-	1.596	-

Table 5 Representative mineral analyses for metasediments from Val Sessera (IV160), Val Strona di Postua (IV346) and Val Strona (IV385, IV381, IV383, IV384). (c) refers to grain centres, (e) to grain edges and (inc) to biotite inclusions within garnet.

ROCK	IV160		IV346				IV385				
MINERAL	GT	PLAG	GT	OPX	PLAG	BI	GT(c)	GT(e)	BI(inc)	BI	PLAG
SiO2	39.2	59.0	39.29	50.96	60.17	36.57	38.3	38.2	36.0	36.3	59.4
TiO2	-	-	0.03	0.12	-	5.94	-	-	3.5	3.7	-
Al2O3	22.3	25.6	21.77	2.95	24.38	14.34	21.7	21.5	18.6	18.9	24.8
Cr2O3	-	-	-	0.06	-	0.08	-	-	-	-	-
FeO	28.4	-	29.84	26.89	-	15.64	32.4	32.3	14.2	16.2	-
MnO	0.3	-	1.27	0.39	-	0.02	1.7	1.8	-	-	-
MgO	10.1	-	7.79	18.89	-	12.62	6.4	5.9	12.8	11.2	-
CaO	1.3	7.9	1.74	0.21	7.43	0.00	1.2	1.0	-	-	5.6
Na2O	-	6.6	-	-	7.25	0.07	-	-	0.7	-	7.9
K2O	-	0.2	-	-	0.36	9.90	-	-	8.5	8.7	0.3
TOTAL	101.6	99.3	101.73	100.47	99.59	95.18	101.7	100.7	94.3	95.0	98.0
mg	44.7		31.8	55.6		59.0	26.0	24.5	61.6	55.2	
An		39.4			35.4						27.8
No (O)	12	8	12	6	8	22	12	12	22	22	8
Si	2.962	2.648	3.010	1.928	2.694	5.518	2.982	3.000	5.380	5.419	2.693
Al	1.994	1.353	1.966	0.072	1.287	2.482	1.991	1.989	2.720	2.581	1.325
Al	-	-	-	0.060	-	0.068	-	-	0.556	0.745	-
Ti	-	-	0.002	0.003	-	0.674	-	-	0.393	0.415	-
Cr	-	-	-	0.002	-	0.010	-	-	-	-	-
Fe	1.834	-	1.912	0.851	-	1.973	2.110	2.121	1.775	2.022	-
Mn	0.019	-	0.082	0.012	-	0.003	0.112	0.120	-	-	-
Mg	1.132	-	0.890	1.065	-	2.838	0.743	0.690	2.852	2.492	-
Ca	0.106	0.380	0.143	0.009	0.356	0.000	0.084	0.084	-	-	0.272
Na	-	0.574	-	-	0.629	0.020	-	-	0.203	-	0.694
K	-	0.011	-	-	0.021	1.906	-	-	1.621	1.657	0.017

Table 5 (cont)

ROCK	IV381				IV383						IV384		
MINERAL	GT(av)	BI(inc)	BI(av)	PLAG	GT(c)	GT(e)	BI(av)	BI(inc)	OPX	PLAG	GT	BI	PLAG
SiO2	38.4	36.6	35.6	55.5	38.9	38.5	37.1	37.4	51.6	56.9	39.6	36.2	61.5
TiO2	-	4.9	5.4	-	-	-	5.9	7.2	-	-	-	6.9	
Al2O3	21.4	16.9	16.9	28.4	22.0	21.8	14.9	14.9	1.9	27.0	22.4	15.9	24.5
Cr2O3	-	-	-	-	-	-	-	-	-	-	-	0.3	-
FeO	32.5	13.8	16.6	-	29.0	27.9	13.5	12.1	24.7	-	27.8	10.8	-
MnO	1.1	-	-	-	0.6	0.7	-	-	-	-	0.4	-	-
MgO	5.8	14.0	11.6	-	7.5	6.7	14.0	13.7	20.4	-	10.2	15.2	-
CaO	2.0	-	-	11.4	3.6	4.8	-	-	0.3	9.0	1.3	-	6.2
Na2O	-	-	-	5.2	-	-	-	-	-	6.2	-	-	7.9
K2O	-	9.1	8.2	-	-	-	8.9	8.6	-	0.2	-	8.7	-
TOTAL	101.2	95.3	94.3	100.5	101.6	100.4	94.3	93.9	98.9	99.3	101.7	94.0	100.0
mg	24.1	64.4	55.5		31.5	30.0	64.9	66.9	59.6		39.5	71.5	
An				54.8						54.8			30.5
No(O)	12	22	22	8	12	12	22	22	6	8	12	22	8
Si	3.001	5.416	5.379	2.488	2.983	2.988	5.543	5.559	1.960	2.567	2.990	5.363	2.725
Al	1.971	2.584	2.621	1.501	1.988	1.994	2.457	2.441	0.040	1.436	1.993	2.637	1.280
Al	-	0.344	0.388	-	-	-	0.166	0.170	0.045	-	-	0.140	-
Ti	-	0.545	0.614	-	-	-	0.663	0.805	-	-	-	0.769	-
Cr	-	-	-	-	-	-	-	-	-	-	-	0.035	-
Fe	2.124	1.708	2.098	-	1.860	1.811	1.686	1.504	0.784	-	1.755	1.388	-
Mn	0.073	-	-	-	0.039	0.046	-	-	-	-	0.023	-	-
Mg	0.676	3.088	2.612	-	0.857	0.775	3.117	3.306	1.155	-	1.148	3.357	-
Ca	0.168	-	-	0.548	0.296	0.399	-	-	0.012	0.435	0.105	-	0.294
Na	-	-	-	0.452	-	-	-	-	-	0.542	-	-	0.670
K	-	1.718	1.581	-	-	-	1.696	1.631	-	0.012	0	1.695	-

Table 6 Pressure and temperature estimates for metasedimentary rocks. The temperatures in brackets under the pressure estimates are the temperature range for which the calculation was made. (c) - temperature estimate from garnet grain centres and biotite inclusions; the remaining temperatures were calculated for average analyses or grain edges. N + P (1982) is the gt = plag + opx + qz geobarometer of NEWTON & PERKINS (1982); N + H (1981) is the plag = gt + sill + qz geobarometer of NEWTON & HASELTON (1981); F + S (1978) and THO (1976) are for the garnet-biotite thermometer of FERRY & SPEAR (1978) and THOMPSON (1976) respectively. GRAIL is the garnet-rutile-ilmt-sill-qz-geobarometer quoted in ESSENE (1982).

METHOD	N+P(1982)	N+H(1981)	F+S(1978)	THO(1976)	GRAIL
IV160		4.7-5.9 (700-800)	780		6.0
IV346	5.9-6.4 (700-800)		720	660	
IV101	8.3-8.9 (800)				
IV385		4.5-6.5 (650-750)	800(c) 600-720	720(c) 570-670	
IV381		4.8-6.9 (650-750)	760(c) 660-700	700(c) 620-640	
IV383	5.8-7.0 (650-750)		810(c) 630-680	725(c) 600-640	
IV384		5.0-7.0 (650-750)	730-750	670-690	6.5-7.1 (650-750)